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DOI:10.1109/BMSB.2018.8436927

An Integrated, Virtualized Joint Edge and Fog Computing System with Multi-RAT Convergence

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Abstract— **Notably, developing an innovative architectural network paradigm is essential to address the technical challenging of 5G applications' requirements in a unified platform. Forthcoming applications will provide a wide range of networking, computing and storage capabilities closer to the end-users. In this context, the 5G-PPP Phase two project named "5G-CORAL: A 5G Convergent Virtualized Radio Access Network Living at the Edge" aims at identifying and experimentally validating which are the key technology innovations allowing for the development of a convergent 5G multi-RAT access based on a virtualized Edge and Fog architecture being scalable, flexible and interoperable with other domains including transport, core network and distant Clouds. In 5G-CORAL, an architecture is proposed based on ETSI MEC and ETSI NFV frameworks in a unified platform. Then, a set of exemplary use cases benefiting from Edge and Fog networks in near proximity of the end-user are proposed for demonstration on top of connected car, shopping mall and high-speed train platforms.**

Keywords— Cloud, Edge, Fog, RAN, MEC, NFV, multi-RAT, 5G.

I. INTRODUCTION

This paper is intended to provide an overview of architecture design, use cases, and testbeds in the framework of the 5G-PPP Phase 2 project termed "*5G-CORAL: A 5G Convergent Virtualized Radio Access Network Living at the Edge*" [1]. A new architectural network paradigm is needed in order to support 5G applications (e.g. augmented reality, connected vehicles, remote operations, and robotics) and to satisfy their extremely challenging technical requirements like end-to-end latency below 1ms and transmission reliability very close to 100%. This cannot be accomplished by a completely centralized architecture, which mainly addresses the need to cope with the dramatic user traffic increase in mobile networks.

The 5G system, however, is expected to provide a wide range of services with bandwidth-intensive and/or delay-sensitive requirements, hence not limited to mobile broadband [2] [3]. These services require networking, computing and storage capabilities to be provided closer to the end-users, i.e. in the Edge of the mobile network. It is here where users' data originates and needs to be collected, processed and possibly sent to other nearby users, hence leading to the concept of the Intelligent Edge. A broad set of techniques allowing for these capabilities to be moved out of remote centralized data-centers (i.e. Clouds) has been defined in the context of ETSI MEC [4] in order to meet stringent requirements, like the ones from Vehicle-to-Everything (V2X) communications.

The approach as illustrated above, however, cannot be implemented without considering the Network Functions Virtualization (NFV) framework, also developed by ETSI [5] [6]. By means of NFV, both fixed and mobile network functions can be software-implemented, hence becoming virtual network functions (VNFs) to be then instantiated by the operator on commodity off-the-shelf (COTS) servers by exploiting virtualization technologies.

The need for Edge computing in IoT applications was addressed by the so-called Fog computing architectural paradigm [7]. This because there was the need to properly handle the significant amount of data originated by "things" at the Edge which negatively impacts mobile network performance in terms of both required bandwidth and latency.

This issue can be solved by allowing data processing and applications to be concentrated locally in smart devices rather than being performed in the Cloud. Actually, not only applications but also networking functions can benefit from low latency offered by Edge and Fog paradigms when executed close to the end-users' devices and things. Therefore, Edge and Fog can allow not only (virtualized) RAN but also transport and core network functions to be executed in the Edge and Fog so as to save bandwidth in their respective domains and offer local breakout when needed. For instance, core network functions (e.g., MME), virtualized in the Edge and Fog platform closer to the end-users, can be implemented aiming at facilitating data offloading and mitigating heavy-signaling caused by frequent handovers in the local access.

The wireless network also has to address the need to offer connectivity to various types of devices and services in a given local area. Therefore, a variety of Radio Access Technologies (RATs) having different characteristics in terms of capacity, spectral efficiency, mobility support, complexity and costs needs to be integrated into a common framework, realizing the so-called multi-RAT convergence [8]. Integration of RAN functions belonging to various RATs (e.g., 5G NR, 4G LTE, WiFi, Narrow Band IoT, Bluetooth Low Energy, ZigBee and so on) within an Edge and Fog virtualized architecture enables simpler and cheaper networks to be realized via re-use of common functionalities and infrastructure, also extending the service coverage of one RAT to areas where other RATs are available without the need to deploy additional network equipment (e.g. base stations).

Quality-of-Experience (QoE) can always be ensured by the possibility to select dynamically the best-suited RAT for the service(s) the user is requesting. Another important aspect addressed in the project is the need to consider computing, storage and network resources being provided by any Edge/Fog node or device on the move and regardless of the respective owners. This goes beyond the ETSI MEC, where a fixed and centralized location for the Edge platforms owned by only one stakeholder (i.e., the operator) is considered.

To summarize, 5G-CORAL aims at identifying and experimentally proofing – through trials on large-scale testbeds – which are the key technology innovations enabling the development of a virtualized Edge and Fog architecture with multi-RAT convergence which is also scalable, flexible and interoperable with other domains including transport, core network and distant Clouds. This architecture will fulfill several of the ITU-R objectives for 5G [9] and 5G-PPP programme Key Performance Indicators (KPIs) [10]:

- *Increase the data rate* by exploiting tight coordination and convergence among multiple RATs co-existing in the same service area.
- *Increase traffic volume density* thanks to dynamic reconfiguration of resources usage among the Edge and Fog networking and computing elements in order to serve local areas with higher demands.
- *Increase spectrum efficiency* by means of traffic offloading from one RAT to another, RAT configuration adaptation based on context information from other RATs, aggregation across RATs, assistance and sharing among RATs, tight coordination among Edge/Fog nodes and devices from multiple RATs for interference mitigation and radio resource management.
- *Increase connection density* by providing a platform being able to serve a number of heterogeneous devices.
- *Reduce latency* by dynamically moving functions and services as close as possible to the user.
- *Improve energy efficiency* via reduction of power consumption enabled by sharing and pooling of the networking and computing resources available at the Edge, offloading of computing- and/or networking-intense functions from the end-user devices to the Edge, and smart coordination of devices for minimizing the number of transmissions.
- *Enhance mobility* by taking into account mobility management issues arising from moving end-users' devices whose resources can be dynamically added/removed to/from the global resource pool.

The paper is structured as follows: firstly, the challenges related to the integration of Cloud, Edge and Fog systems within a unified platform are addressed in Section II by also considering multi-domain federation aspects. Then, in Section III, an initial architecture foreseen in the context of 5G-CORAL is described based on ETSI MEC and ETSI NFV frameworks. Section IV illustrates a set of use cases taken into consideration for developing both the architecture and the demonstration platforms allowing for the experimental validation of the 5G-CORAL solution. Finally, Section V draws the conclusions.

II. Paradigm of Cloud, Edge and Fog integration

This paper addresses a new concept of computing for 5G and beyond, which essentially integrates computing resources in the domains of Cloud, Edge, and Fog to assist 5G delivering the services satisfying various types of KPIs. In this section, we will first review the state-of-the-art for both Cloud and Edge computing, which has been intensively investigated during the last decade. Then, the challenges of further federating Cloud, Edge, and Fog will be inspected. The section will also discuss how this new computing platform is able to achieve multi-RATs convergence.

A. Background of Cloud and Edge Computing

The last decade has seen Cloud computing as the promising paradigm for computing. It centralizes storage, compute, and network, as data-centers, backbone IP networks, and cellular core networks [11]. Resources available in the Cloud can be leveraged to provide elastic compute, storage and networking to the application running on top of it and resource-constrained user devices. Cloud computing has become the driving factor of rapid growth for some business.

A new trend is rising in computing, i.e., Edge computing that enables the compute, storage and networking resource in the proximate distance of the end-user. Recently, there have been many proposals for the operation and architectural design for the Edge computing. Multi-access Edge Computing (MEC) [12], Fog Computing [13], Cloudlet [14] and Mobile Cloud Computing (MCC) [15] are all hot topics in the literature. All the proposals define the various practical implementation of Edge computing with different goals, such as MEC target the

Telecommunication sector whereas Fog Computing, Cloudlet and MCC target IoT, Mobile Gadgets and wearable technologies. Aim of Edge computing is to enrich user satisfaction and improve QoE. Edge computing increases the Edge responsiveness by hosting/offloading the applications and services [16] [17] [18] [19], which are present at one hop, through access technologies. At the same time, subset of requests can be forwarded to the traditional Cloud computing through Wide Area Network (WAN) which are not latency sensitive.

B. Federation with Fog

Federation can be defined as the process of integrating multiple administrative domains at different granularity into a unified platform where the federated resources can trust each other at a certain degree, whereas the federation trust is the embodiment of a service-/business-level agreement or partnership between two organizations [20]. Federation has already been explored as a viable path for integrating multiple Cloud infrastructures, either public or private, with the goal of matching business needs. Remarkably, federation increases consumer value for and facilitates providing IT services as a commodity [21].

Recently, Fog computing has gained considerable traction because of the increasing adoption of IoT and of the issues of centralized Cloud architectures when applied to IoT scenario: the large amount of data generated by IoT needs to traverse all the network to reach the Cloud, thus resulting in high-bandwidth consumption and non-predictable latency experienced by the IoT system [22]. Therefore, Fog computing aims at processing IoT data where it is generated by creating an intermediate computing layer between devices and Cloud. However, Fog is meant to be complementary to the Cloud and not to replace it. To further integrate Cloud and Fog, an integration mechanism has been proposed in [11]. However, the work focuses on IT scenarios and does not consider networking scenarios (e.g., mobile networks) nor the business dynamics involved in the federation process.

C. Enablement of Multi-RATs Convergence

This is already quite common nowadays that mobile user devices are exposed to heterogeneous RATs simultaneously (e.g. New Radio (NR), LTE, WiFi, and Bluetooth). To maximize the system efficiency in a holistic manner, it is envisaged that coordination among multiple RATs will become even more crucial in 5G and beyond. This can be testified by the trend of some new 3GPP LTE mechanisms that aimed to exploit unlicensed spectrum to increase the achievable peak data rate. For example, License-Assisted Access (LAA) [23] will take the status of co-existing WiFi radio access into account (by “listen before talk” or LBT) for interference avoidance. In some cases, multi-RATs can be even more closely integrated with a radio-agnostic framework, which allows multiple RATs to share a common control plane and/or higher-layer protocol stack (e.g. PDCP in LTE). Thus, offloading of user plan traffics can be realized by dynamic switching between the RATs, and data throughput may also be boosted via aggregation.

As envisioned by MEC [24], the benefits of Edge computing can be enjoyed by more than one types of access technologies. Through the integration of Cloud, Edge and Fog, we aim to open a new dimension of multi-RATs convergence. In particular, we may freely host the VNFs of different RATs at more appropriate place (e.g. Cloud or Edge) according to the instantaneous system or user status. Furthermore, as context information pertaining to each RAT may be accessible by the other RATs on this integrated computing platform, they may be able to configure themselves in a more judicious fashion based on the information, hence facilitating multi-RATs convergence more efficiently. For example, if the cellular system (e.g. LTE) is able to know or even predict the traffic status of WiFi with certain information, cellular users may access unlicensed band with more agility without going through cumbersome LBT procedures. In addition, through analysis of various types of data gathered by IoT sensors, this integrated platform among Cloud, Edge and Fog is able to offer certain meta-data that may be required by optimization algorithms among multiple RATs. In short, tight coordination for multi-RATs can be conducted by using this brokerage platform.

III. ARCHITECTURE DESIGN

The design of the integrated Fog, Edge and Cloud system, namely 5G-CORAL architecture, follows the ETSI MEC and ETSI NFV concepts and envisages a mix of physical and virtualized resources available on the Fog and Edge devices to form an ETSI NFV compliant infrastructure. Fig. 1 presents the initial idea of the proposed architecture. It contemplates two major building blocks, namely *(i)* the Edge and Fog computing System (EFS) subsuming all the Edge and Fog computing substrate offered as a shared hosting environment for virtualized functions, services, and applications; and *(ii)* the Orchestration and Control System (OCS) responsible for managing and controlling the EFS, including its interworking with other (non-EFS) domains (e.g., transport and core networks, distant Clouds, and so on).

The EFS building block is formed by three main elements: *i)* EFS Applications, *ii)* EFS Functions and *iii)* EFS Service Platform. EFS Applications perform computing and/or networking tasks for the end-user or a third party. EFS Applications can consume and/or publish information through one or more services. Examples of EFS Application might be an augmented reality application or a Fog node coordinator. EFS Functions perform computing and/or networking tasks required for network operations and/or performance enhancements. An EFS Function can consume and/or publish information through one or more services and can interact with one or more applications. Examples of function are a Base Band Unit (BBU) and a Mobility Management Entity (MME). Finally, EFS Service Platform provides information through publish/subscribe or request/reply system. This information can be published or consumed by functions and/or applications which are either part or external of the EFS. An example of EFS Service is the radio network information service from ETSI MEC [4]. Such service could be provided either by a virtualized BBU (vBBU) through the E2 interface or by a physical eNodeB through the T8 interface.

According with the ETSI NFV architecture, each of the EFS Applications, Functions and Services may have an Element Manager which is in charge of applying the configuration and management policies as defined by the EFS

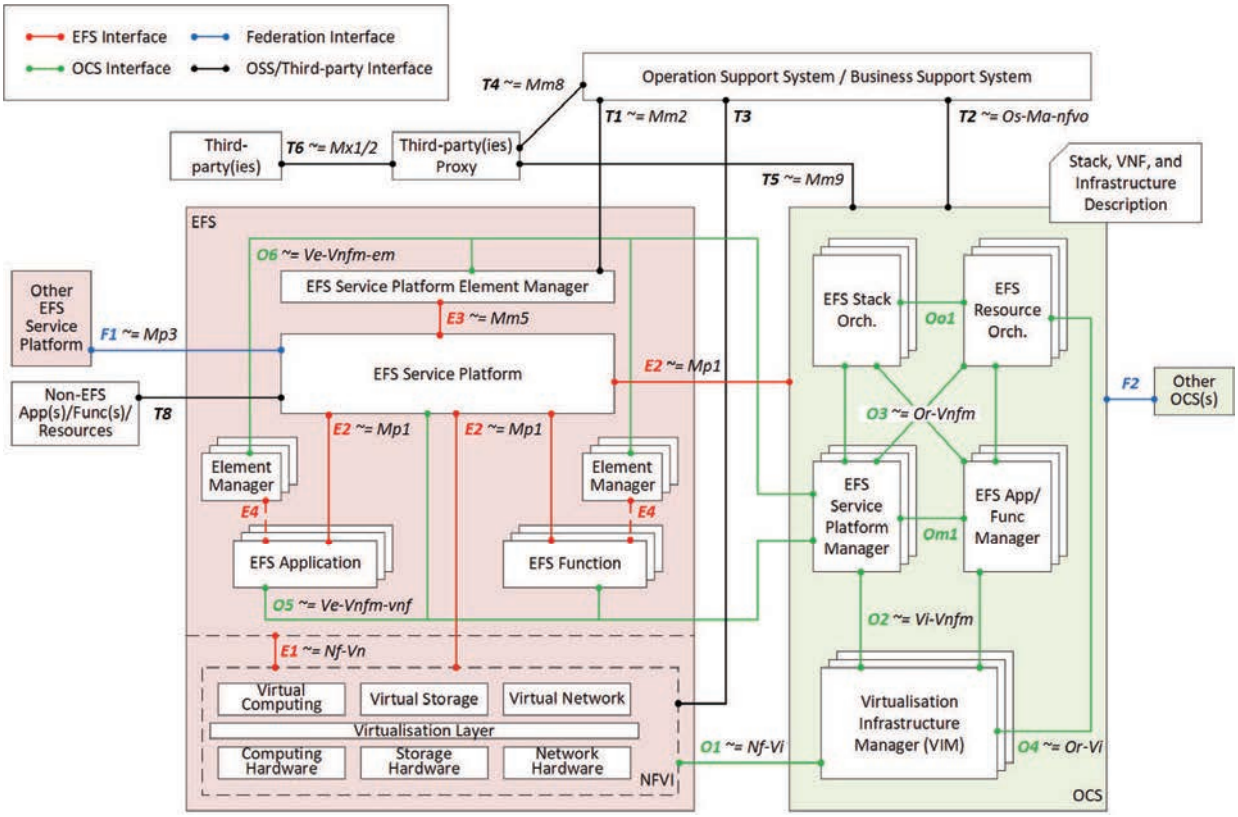

Fig. 1. 5G-CORAL architecture.

Manager at the OCS (interface O6, functional similar to ETSI NFV Ve-Vnfm-em [4]). The Element Manager of the EFS Service Platform partially plays the role of the ETSI MEC Platform Manager [12]. Its scope is limited to service-related management only (e.g., policies configuration) and is not in charge of the lifecycle management of the applications and functions which is instead the responsibility of the OCS. The different EFS components are designed to run in an amalgam of devices, with different capabilities and features. EFS functionality will partially reside in Fog devices distributed near the user, access nodes, incorporating multiple technologies and virtualized infrastructure in servers located at the Edge.

The OCS design follows the ETSI NFV architecture and comprises the following components: *i)* EFS Orchestrator, *ii)* EFS Manager and *iii)* Virtualized Infrastructure Manager (VIM). As in the ETSI NFV architecture, the Orchestrator takes care of building the end-to-end service, by requesting the underlying modules to instantiate the required VNFs, EFS Applications and Functions. This task is accomplished by the EFS Stack Orchestrator. Resources are instead orchestrated by the EFS Resource Orchestrator which keeps track of the status of all the resources composing the system. The EFS App/Func Manager manages the lifecycle of the Applications, Functions, and Services, including migration and on-demand scaling while the EFS Service Platform Manager manages the lifecycle of the service platform itself. Finally, the VIM is in charge of managing the virtualized infrastructure as in ETSI NFV architecture. Operations in the scope of the VIMs are keeping an inventory of available resources (including their discovery) and managing the connectivity of the various Applications, Functions, and Services. The key functionality of the OCS is to build a coherent view of the EFS capabilities in a certain area considering the different resources and access technologies deployed.

IV. USE CASES EXAMPLES AND DEMONSTRATION PLATFORMS

This section presents the use cases and demonstration scenarios identified within the integrated solution of Edge and Fog computing system.

A. *Use cases examples*

There are many services that could benefit from being hosted in the near proximity of the user. In combination with visibility into distributed private Fog networks to more centralized Edge networks. Some of the leading use cases are discussed as follows:

Safety in Connected Cars: cars and other vehicles may exploit 5G and legacy wireless communications to improve traffic safety, to support drivers with real-time information on road and traffic conditions, and to make the mobility of emergency vehicles such as ambulances and fire trucks safer [25]. This information is received by the vehicles nearby and can be used to alert all the drivers about what is going on the road. Such category of communications includes different ways: a Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I) communication, a communication with vulnerable road users, e.g. pedestrians and cyclists (Vehicle-to-Pedestrians, V2P). The related applications can be hosted distributed on the Edge and Fog systems, to optimize the network performance such us offloading and end-to-end network latency, then taking full advantage of the low latency communications at the EFS.

Smart City Services: in smart cities, jointly orchestrated Edge and Fog computing systems can enhance multiple use cases such as security cameras vision and face recognition offloading, and smart traffic light system. In particular, security cameras vision and face recognition specific use case using of Edge and Fog systems to offload face recognition and computer vision algorithms to a resource-sufficient Cloud environment, taking advantage of low latency communication and high bandwidth environment that the Edge/Fog provides. Furthermore, offloading to the joint Edge and Fog system will increase the number of connected devices as the price per device will greatly reduce. In addition there is the smart traffic light system use case, where street lights jointly with cameras control the traffic in a certain region, in order to maintain a continuous flow of pedestrians and vehicles. Additionally, it could be able to prevent accidents and collect traffic statistics in order to improve the system globally.

Wireless High-Speed Train Services: in high-speed train, wireless train services can be optimized by utilizing the Edge units. In particular, end-users can benefit from cached information on the on-board Edge server where required data is collected based on user demands. When a train is stationed, the on-board Edge server exchanges (adds/deletes/updates) information with the updated one from on-land server located in every station. The fact of having computational and networking resources locally in the train and their capacity to update and cache information on the stations open the door to novel applications taking benefit of the locality of the data. Examples of these applications are smart tourism guides (city information, 3D interactive offline city maps and points of interest), updated news (also based on the location of the train) or interactive train services (customer service, emergency, e-routes based on user's destinations).

Robot and Augmented Reality in Shopping Mall: various tasks in a shopping mall could be handled by robots to enhance experiences of the customers. For examples, we may have (1) robots that guide customers to the shops of interest, (2) robots that help customers to fetch merchandises, (3) robots that provide personal assistance to the disabled customers, (4) robot security guards, and (5) robots that maintain and perform operational tasks on behalf of the shop owners. Many of these potential use cases require tight cooperation among robots, or even between robots and humans. Conventionally, Cloud robotic [26] could be employed, in which multiple sensors distributed across the shopping mall building collect raw data for Cloud processing, to derive the instructions for the robots. Nevertheless, in some cases extremely low latency is needed and Cloud robotic may not be feasible due to intolerable delay. Also, Augmented Reality (AR) applications can be deployed in the shopping mall to improve the user experience of the customers and the workers. For example, (1) Live Navigation, to provide accurate and live navigation to the destined shop, (2) Repair and Maintenance, where AR can be used to overlay instructions to reduce error-rates, (3) connecting remote workers, allows an expert or the shop owner to assist his workers to complete the task remotely, (4) additionally shoppers can also use the AR to see how the object will look like.

IoT: the current IoT solution is based on a client/server design where client softwares (SWs) are running on the devices or gateways and server SWs are running in the Cloud. The latency becomes an issue for many real-time industrial IoT applications. For example, wireless robotics can require ms-level of latency. Edge and Fog computing provides the opportunities to provide a low latency computing infrastructure to end-users. The Fog nodes can host the light-weight computing and networking tasks with the lowest possible latency. The Edge nodes usually have more computing, storage, and networking resources and thereby can act as a nearby small scale Cloud providing heavier services like data analytics, and coordinate and management of a huge amount of IoT devices. It may also provide the users additional values when data from different IoT networks are available and thereby can be co-processed in the Edge and Fog. For example, data from the presence sensors may be useful to improve the accuracy of the localization service, or to dynamically turn on/off resources at the Edge to save energy.

B. Demonstration platforms

This subsection highlights the demonstration platforms, where appropriate use cases will be selected for demonstrations in the following listed real-world platforms.

Connected Cars: the testbed is located in Turin, Italy. The Connected Cars testbed will support the trial for those use cases that exploit the Connected Cars' communication through the cellular infrastructure (V2I). In this scenario, data regarding speed, direction and position are collected from vehicles and can be used in different ways for improving the cars safety. In fact, the V2I communications add significant value to the advanced driver-assistance systems in terms of improved safety, traffic optimization and improved driving experience. Within the suggested testbed setup, it could be possible to consider a number of different end-user applications such as road works reporting, weather conditions reporting, emergency vehicles approaching, position tracking and collision avoidance.

Shopping Mall: the testbed is located in Taipei, Taiwan. It provides facilities for performing experiments and pilot deployments in realistic dense scenarios, both regarding infrastructure and users. The testbed also allows users to take part in the demonstration trials. Computation offloading, network offloading and mission-critical services will be demonstrated in a multi-RAT dense environment. For instance, AR and Robotics will benefit from location and multi-RAT context information. Also, IoT gateways and AR applications will take advantage of the vicinity of computing resources for offloading heavy processing tasks from end-user devices/sensors to the Edge/Fog computing devices to leverage the low latency communications.

High-Speed Train: the testbed is located in Hsinchu, Taiwan. It is amongst very few commercial high-speed train testbeds in the world capable of collecting and experimenting real high-speed data on real scenarios. The envisioned goal of this testbed is to verify seamless connection in the high-mobility scenario. One anticipated goal is to provision breakout and mobility functions on the Edge/Fog that could potentially mitigate the burden of passenger's mobility signaling on the backhaul.

V. Conclusions

In this work, challenges related to the integration of Cloud, Edge and Fog systems within a unified platform were addressed. While addressing these challenges, the initial design of a unified platform architecture which can integrate and federate the Fog and Edge were proposed. This architecture is based on ETSI MEC and ETSI NFV frameworks and targets 5G KPIs such as increasing the data rate, increasing spectrum efficiency, reduction in latency and mobility enhancement. Based on 5G-CORAL architecture, several use cases were presented benefiting from being hosted in the Edge and distributed private Fog networks in a near proximity of the end-user. Finally, the demonstration testbed platforms were presented to validate the expected solution on top of the 5G-CORAL architecture.

Acknowledgment

This work has been partially funded by the H2020 collaborative Europe/Taiwan research project 5G-CORAL (grant num. 761586).

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